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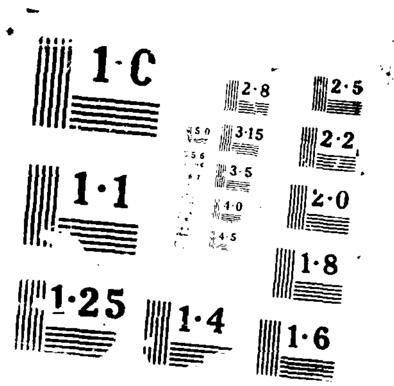
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The overall goal of this project is to study convective heat transfer and fluid-mechanics in a concavely curved turbulent boundary layer. The objective is to identify the mechanisms whereby concavity increases surface heat transfer. Progress during the past year has centered on the recently added goal of studying the combined effects of moderate levels of grid-generated turbulence and concave curvature. Overall results from the fluid-mechanics section of the project are that grid-generated turbulence increases the skin friction, but does not alter the near-wall mean velocity scaling or the near-wall levels of the velocity fluctuations. The heat transfer measurements are showing that the Stanton number is increased by the grid-generated turbulence with the combined effects of curvature and the additional turbulence producing the largest increase.

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10 March 1988

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1. Goals

1.1 Introduction

Kreith* first showed, in 1955, that concave curvature increased heat transfer, although the fact that curvature affected the turbulence structure had been known since the early 30's. Between 1955 and 1967, there does not appear to have been much activity. In 1967 Schneider and Wade measured heat transfer in a curved-duct flow, and in 1968 Thomann made local measurements of boundary-layer heat transfer in a supersonic flow with convex and concave curvature. In every instance, concave curvature resulted in an increase in heat transfer. The increase was assumed by many to be the direct consequence of streamwise vortices within the boundary layer, caused by a Taylor Gortler instability, but there was dissent. Eskinase and Yeh (1956) reported an increase in heat transfer, but no evidence of streamwise vortices. The issue has become increasingly important as aircraft engine designers have pressed closer and closer to the limits of assurable prediction of heat transfer. It is desirable to be able to predict the heat-transfer coefficient within 5% on a turbine blade, yet this cannot be done at the present state of the art. Most of the current prediction programs for boundary-layer heat transfer are two-dimensional. If Taylor-Gortler vortices are important in the concave-wall boundary layer, then three-dimensional codes will have to be developed. On the other hand, if the increase in heat transfer is a result of a generally increased turbulence activity, but still two-dimensional, then existing codes can be simply modified to acknowledge the curvature effect, and no major changes in computational philosophy need be undertaken.

The objective of this work is to identify the mechanism whereby concave curvature increases the heat transfer through a turbulent boundary layer. This involves careful documentation of the fluid mechanics and of the heat transfer. It is necessary to establish a well-qualified flow on a concave surface, demonstrate that the heat transfer is increased, and then determine the fluidmechanic and thermal behavior of the boundary layer carefully enough to establish whether or not streamwise vortices played an important role. As in most convective heat-transfer problems, the fluid mechanics must be thoroughly understood before the heat-transfer study can be begun.

1.2 Objectives of the Fluid-Mechanics Study

As a result of the past work on this project (Jeans and Johnston 1982, 1983, and Barlow and Johnston 1985) a much clearer picture of the effects of concave curvature on turbulent boundary layers has emerged. With a better understanding of concave curvature, an investigation of the effects of freestream turbulence on concave turbulent boundary layers was begun. This new direction is a relevant one; previous researchers have shown that freestream turbulence over a flat plate can increase skin friction and Stanton number up to 25%. This direction allows us to build on the extensive data base compiled by Barlow, so that the effects due to freestream turbulence can be separated from those due to streamwise curvature.

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*References listed here are in Reports HMT-35 and MD-47, listed at the end of this section.

The objectives of the 1987 calendar year were to:

1. Complete the installation, development, and qualification of a three-component LDA system using the existing Argon-Ion LDV system for U and V measurement and a recently purchased He-Ne fiber optics probe for W measurement.

2. Continue studying the effects of enhanced levels of free-stream turbulence on the structure of the turbulent boundary layers on concave and flat walls.

1.3 Objectives of the Heat-Transfer Study

The objectives for the 1987 calendar year were altered in the approved Proposal for Continuation of Research submitted in July, 1987. The modified objectives were:

1. Completion of the aluminum heat transfer surface for the flat and curved test sections.

2. Measurement of baseline Stanton number data.

3. Measurement of the mean and fluctuating temperature profiles in the flat and curved sections.

4. Development of a technique to measure correlations between temperature and velocity fluctuations.

5. Dye injection and/or hydrogen bubble flow visualization of large scale inflow and outflow regions in the curve.

6. Construction of one flat and one curved liquid crystal panel to be used with the new heat transfer surface.

7. Examination of the Simonich film to determine thermal sublayer streak spacing and an average heat transfer coefficient on the plate.

2. Accomplishments

2.1 Fluid Mechanics

A detailed study of the effects of concave turbulent boundary layers using two-component laser velocimetry was completed by Barlow and Johnston in 1985. The purchase of a He-Ne laser and fiber optics probe enables us to complement the previous study by making spanwise velocity measurements.

The coupling of the laser beam into the fiber optics cable was straightforward, and transmission efficiencies greater than 40% were achieved. Once alignment was complete, the coupling optics required only occasional re-adjustment to maintain peak power output. The probe has proved to be highly versatile and is easily transferred between the two facilities in which it is used.

The new He-Ne probe is mounted in the channel downstream of the Argon-Ion U (streamwise) and V (normal) component measuring volumes. It is positioned to measure

spanwise velocities. A manual x-y-z traverse was constructed and used to mate the probe's measuring volume with the two other measuring volumes. The probe is angled slightly toward the wall, allowing near wall W (spanwise) measurements without contamination from either U or V velocities. Once alignment is complete, the entire five-beam system is traversed together as a unit.

A new, personal computer based acquisition system with four channel sample and hold capability was installed and calibrated. The acquisition board is used to make velocity and temperature measurements, as well as control the traversing systems.

A first set of simultaneous three component velocity measurements was made in the flat region and at the 60 degree point in the curve. The behavior of the U and V velocities and their cross-products have been well documented by Barlow and Johnston; addition of the fiber-optics probe allows examination of the W component for the first time. At both the flat and 60 degree stations, the mean flow is two-dimensional, resulting in zero mean W. Spanwise velocity fluctuations, w', peaked at $y^+ \approx 40$ at both streamwise locations, with rms levels of .07 U_{pw} and .09 U_{pw} in the flat and curved stations, respectively. The increased fluctuation level at the 60 degree point in the curve is a direct result of the centrifugal instability found in concave boundary layers that results in the formation of streamwise roll cells. Similar increases in the V fluctuation level are detailed in Barlow and Johnston.

The second thrust of the fluid dynamic study is to examine the effects of free-stream turbulence on flat and concave turbulent boundary layers. A square, biplanar grid with mesh spacing (M) to bar diameter ratio (d) of M/d = 5 is used to generate the disturbances. The grid spans the entire channel and is positioned in two locations so as to produce roughly the same level of freestream turbulence ($u'/U_{pw} \approx 5\%$) at both the flat and 60 degree measurement stations. In the description below, the "natural" case refers to flow without the grid in place; freestream turbulence levels for this case were $u' \approx .01$ U_{pw}.

Introduction of the grid caused the mean velocity profiles to be fuller at both measurement locations; skin friction coefficient ($C_f \equiv 2\tau_w/\rho U_{pw}^2$) at the flat station increased by 29% over the flat, natural value, while C_f in the curve increased by 6% over the curved, natural value. When mean velocity is plotted in U^+ - y^+ coordinates (Figure 1a), the profiles collapse below the law of the wall region, which extends out to roughly $y^+ = 70$. This indicates that the usual scaling of U using wall friction velocity u_τ is unaltered by levels of grid-generated turbulence up to the 5% level studied.

The profiles of streamwise velocity fluctuations showed little response to the introduction of grid-generated turbulence (Figure 1b). In both the flat and curved sections, peak fluctuation levels increased slightly, but profile shapes remained unaltered until the freestream was approached. V fluctuations (Figure 1c) showed a stronger response to the grid-generated turbulence. In the curved section, introduction of the grid increased the peak fluctuation level, moved it further out in the boundary layer, and increased fluctuation levels throughout the outer part of the boundary layer. Spanwise velocity fluctuations (Figure 1d) showed a response similar to the V component; the greatest changes were seen for the flow in the curved section. There, fluctuation levels were elevated across the entire boundary layer.

Examination of fluctuation levels near the wall showed that the influence of grid-generated turbulence did not penetrate below $y^+ = 60$. Plots of velocity fluctuations scaled on u_τ showed differences between flat and curved cases, but introducing the grid did not significantly alter the near-wall fluctuation levels.

The added capability of W measurements now permits the complete calculation of the Reynolds stress tensor u'^2, v'^2, w'^2, $u'v'$, $u'w'$, and $v'w'$. The cross-products $u'w'$ and $v'w'$ should be zero in a two dimensional flow, and in the preliminary measurements were negligibly small for $y/\delta_{99} > .25$. Near the wall, these cross-products were non-zero; reasons for this are unknown and are currently under investigation. Addition of the grid to the flat section decreased the values of $u'v'/U_{pw}^2$ below those of the flat, natural case for $y/\delta_{99} > 0.15$. In the curved section, values of $u'v'/U_{pw}^2$ increased above those of the curved, natural case in the outer part of the boundary layer ($y/\delta_{99} > .10$). The near wall ($y+ < 60$) $u'v'$ values for the flat and curved natural cases are slightly lower than those measured by Barlow and Johnston, and work is currently underway to improve measurement techniques so their near-wall values may be checked.

2.2 Heat Transfer

The aluminum heat transfer surfaces have been completed and are now in use in the channel. Baseline Stanton number data have been taken to qualify the surfaces. The flat wall development section data agree with a Stan6 calculation for a flat plate, zero pressure gradient water boundary layer. At the 60 degree point in the curved region, the Stanton number is about 32% higher than at the same streamwise position in a flat plate boundary layer. The Stanton number appears to reach a limiting value in the latter half of the curved section. These measurements agree with the estimates of Stanton number obtained by Simonich using the liquid crystal panels.

A fine wire thermocouple probe has been built and used to measure mean and fluctuating temperature profiles in the flat and curved sections. There is an uncertainty of about two viscous units in the y-position of the probe. This uncertainty will be reduced in the near future. If the position is taken to be consistent with the thermal sublayer correlation ($T+ = Pr\ y+$) then the mean data for the development section agree well with a Stan6 calculation for the same streamwise position. The profiles for fluctuating temperature show a peak of about 16% of the boundary layer temperature difference. This value is consistent with the peak value in u'/U_{pw}. The peak in t' occurs at approximately $y+ = 7$ which is below the expected value of $y+ = 13$ to 15. This shift may be due to the high Prandtl number of 6.5 at the wall.

Measurement of instantaneous correlations between velocity and temperature were attempted using the two component LDA system for measurement of u' and v'. The present observation is that the technique will not work due to fluctuations in the index of refraction caused by turbulence along the three beam paths. Such fluctuations cause the beams to move randomly and the integrity of the measuring volume can not be assured. The boundary layer temperature difference is nominally 3.5 degrees C, and the tabulated variation in index of refraction for water over that range is +/-2 parts in 10,000. This small variation seems to be sufficient to cause an intolerable deflection of the beams. The conclusion is that our LDA system cannot be used to measure velocity in a heated water boundary layer.

A video tape of standard dye injection flow visualization has been made. The tape shows the the near-wall structure in the flat and curved sections and the outflow regions in the curve. Hydrogen bubble flow visualization has not yet been performed.

Construction of liquid crystal panels for the new heat transfer surface has been delayed due to the poor quality of the mylar/gold film heaters used as the heat source and the working surface. An alternate supplier has been found for the heater film and construction will be continued.

The Simonich film has not yet been examined to determine streak spacing. Mean heat transfer coefficient as measured from the films is no longer needed because we now have better measurements of mean h from the new aluminum surface.

The bulk of the measurements beyond those establishing the baseline have been to document the effect on the Stanton number of the introduction of grid-generated turbulence. This work exactly parallels the high turbulence work done thus far in the fluid dynamic study. Figure 2a shows the baseline Stanton number data for the flat development section, a Stan6 prediction for a flat plate water boundary layer, and the data obtained from placing the grid at plate 3. The grid is placed such that a free-stream turbulence intensity of 5% is present at the profile station at the end of plate 6. An increase in St of 34% was measured at the profile station. To document the combined effects of concave curvature and grid-generated turbulence, the grid was placed at plate 5 so that a 5% free-stream turbulence intensity was present at the 60 degree point in the curve at the end of plate 12. Stanton number at 60 degrees was increased by 21% over the value obtained due to curvature alone. The increase due to the combined effects was 59% over the Stan6 prediction for that streamwise location in a flat plate boundary layer. These data are shown in Figure 2b.

Mean and fluctuating temperature profiles for the flat plate baseline case are shown in Figures 2c and 2d respectively. For these plots the probe position was taken so that the sublayer mean data agree with the sublayer correlation. Finally, a comparison of the shapes and thicknesses of the hydrodynamic and thermal boundary layers is illustrated in Figure 2e. The high Prandtl number causes 80% of the boundary layer temperature difference to be contained between the wall and $y^+ = 10$.

3. Reports and Papers from this study

Barlow, R. S., and Johnston, J. P., Roll-Cell Structure in a Concave Turbulent Boundary Layer", AIAA-85-0297, presented at AIAA 23rd Aerospace Sciences Meeting, Reno, Jan 14-17, 1985.

Barlow, R.S. and Johnston, J.P., "Velocity Spectra of Turbulent Boundary Layers on a Concave Surface," Fifth Symposium on Turbulent Shear Flows, Cornell University, Aug. 1985.

Barlow, R.S. and Johnston, J.P., "Structure of Turbulent Boundary Layers on a Concave Surface," Report MD-47, Thermosciences Div., Mech. Engrg. Dept., Stanford, CA 1985.

Jeans, A.H. and Johnston, J.P., "The Effects of Concave Curvature on Turbulent Boundary-Layer Structure," Structure of Comples Turbulent Shear Flow (R. Dumas and L. Fulachier, eds.), Springer-Verlag, 1983, pp. 89-99.

Jeans, A.H. and Johnston, J.P., "The Effects of Streamwise Concave Curvature on Turbulent Boundary-Layer Structure," Report MD-40, Thermosciences Div., Mech. Engrg. Dept., Stanford Univ., June 1982.

Jeans, A.H. and Johnston, J.P., "Turbulent Boundary Layers on Concave Walls," 16 mm film supplement to Report MD-40. Contact J.P. Johnston, Mech. Engrg. Dept., Stanford Univ., Stanford, CA 94305.

Simonich, J.C. and Moffat, R.J., "A New Technique for Mapping Heat-Transfer Coefficient Contours," Review of Scientific Instruments, 53:5, pp.678-683, May 1982.

Simonich, J.C. and Moffat, R.J., "Visualization of the Heat Transfer through a Turbulent Boundary Layer on a Concave Wall," HMT-35, Mech. Engrg. Dept., Stanford Univ., Stanford CA 94305, August 1982

Simonich, J.C. and Moffat, R.J., "Visualized Heat Transfer from a Turbulent Boundary Layer on a Concave Wall," 16mm supplement to Report HMT-35.

Simonich, J.C. and Moffat, R.J., "A Liquid-Crystal Technique for Visualization of Convective Heat Transfer," 16mm supplement to the article in the Review of Scientific Instruments.

3.2 Completed work, current grant

Barlow, R.S. and Johnston, J.P., "Structure of a Turbulent Boundary Layer on a Concave Surface," to appear in 1988 J. Fluid Mechanics.

Barlow, R.S. and Johnston, J.P., "Local Effects of Large-scale Eddies on Bursting in a Concave Boundary Layer," to appear in 1988 J. Fluid Mechanics.

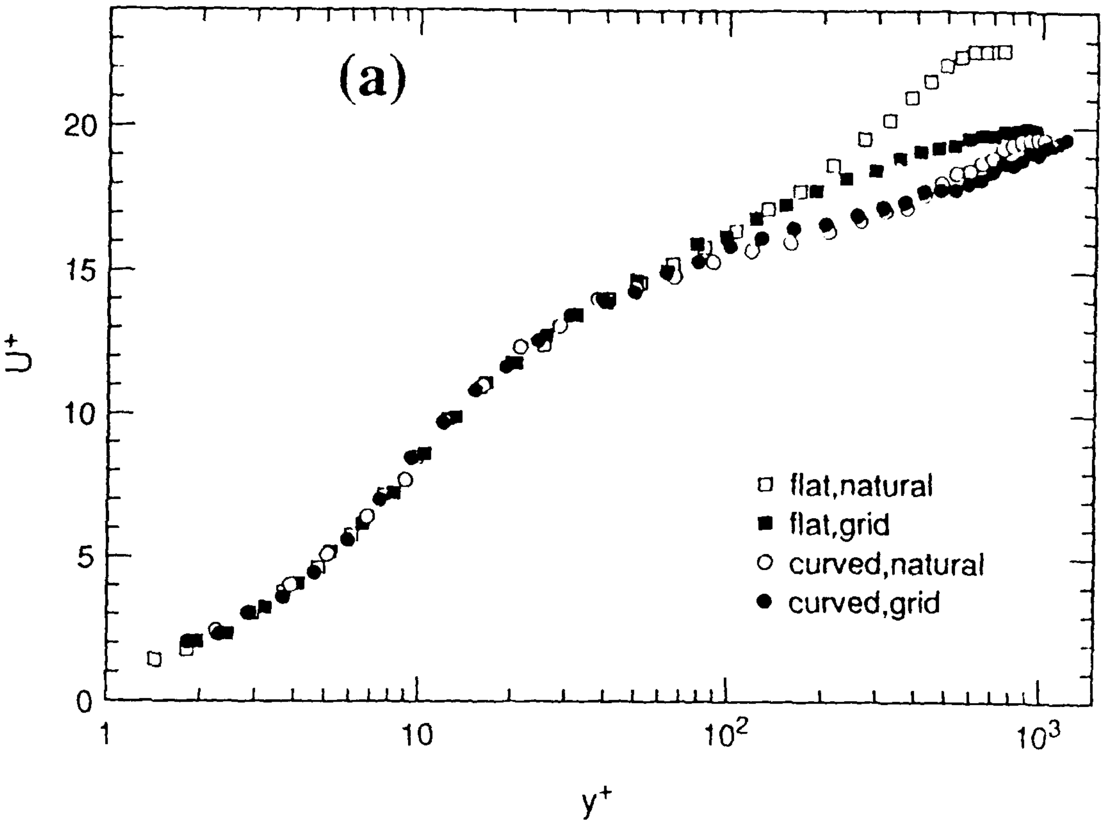

Figure 1a. Mean velocity profile

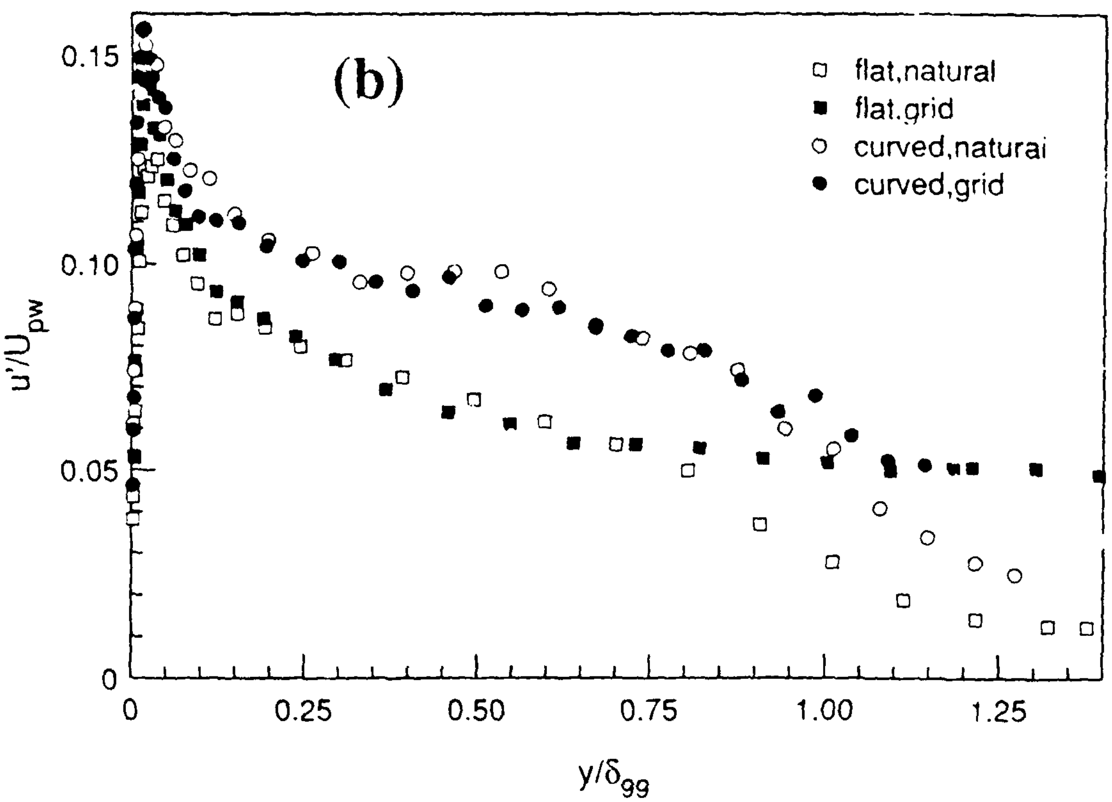

Figure 1b. Streamwise velocity fluctuation profile

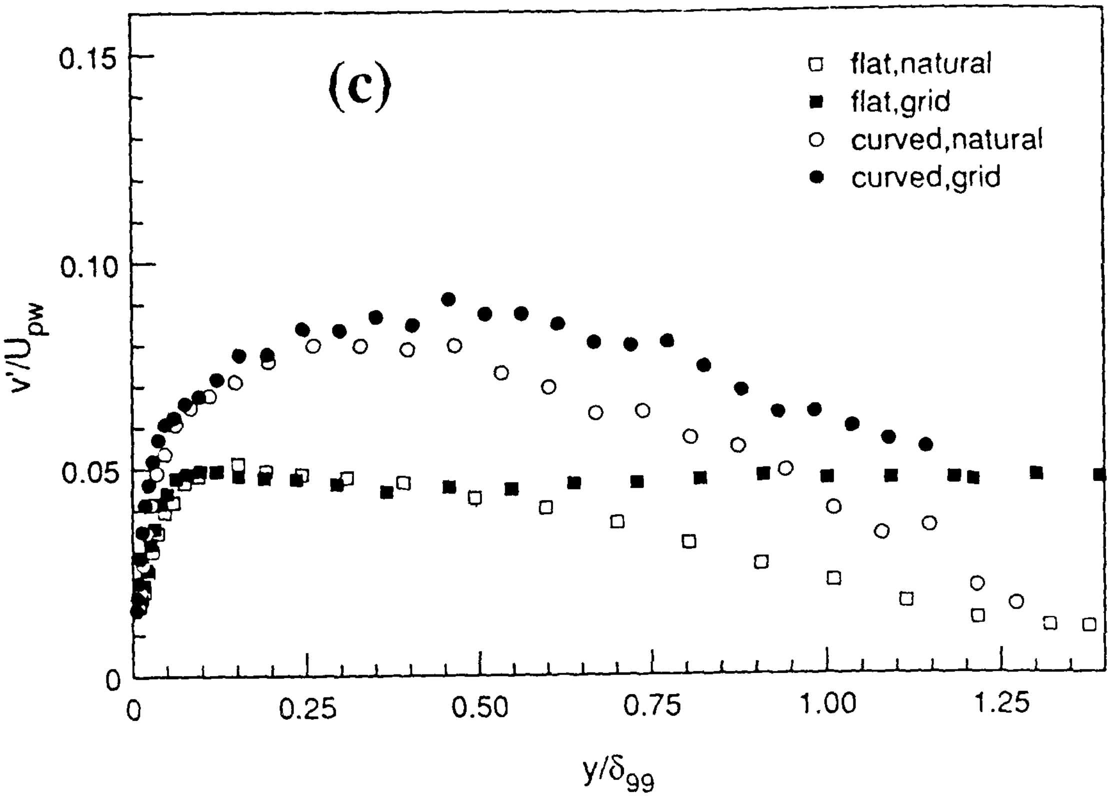

Figure 1c. Normal velocity fluctuation profile

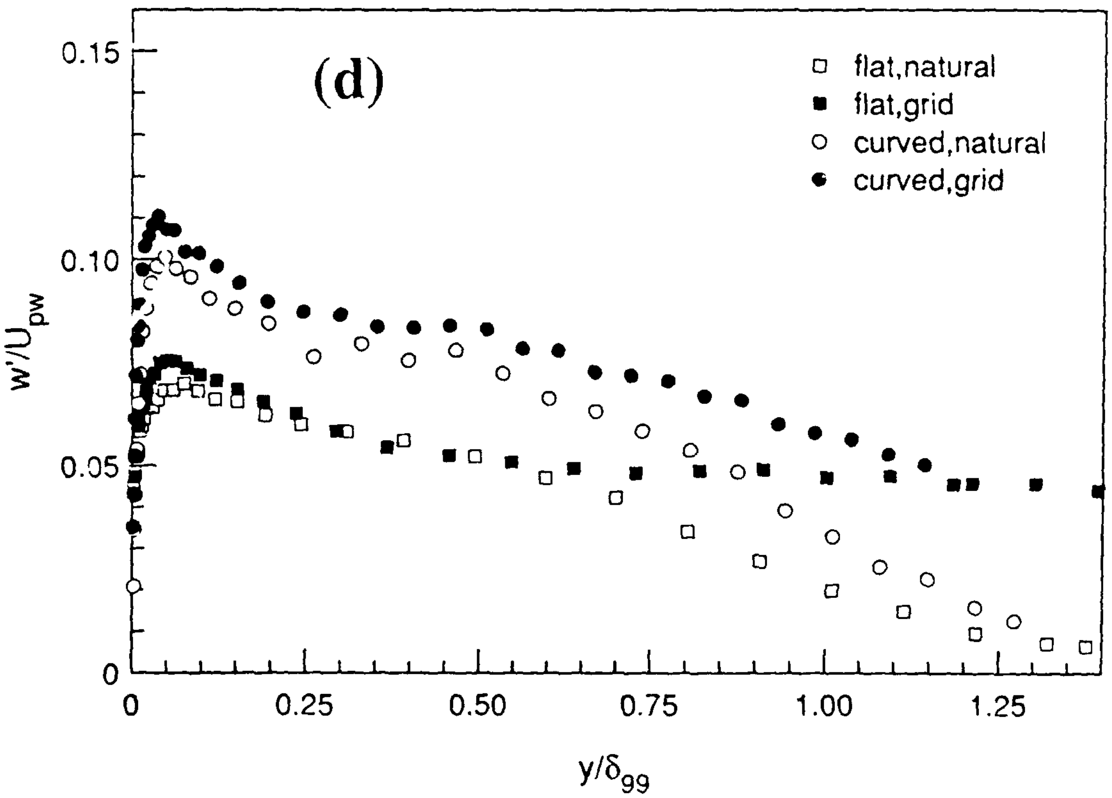

Figure 1d. Spanwise velocity fluctuation profile

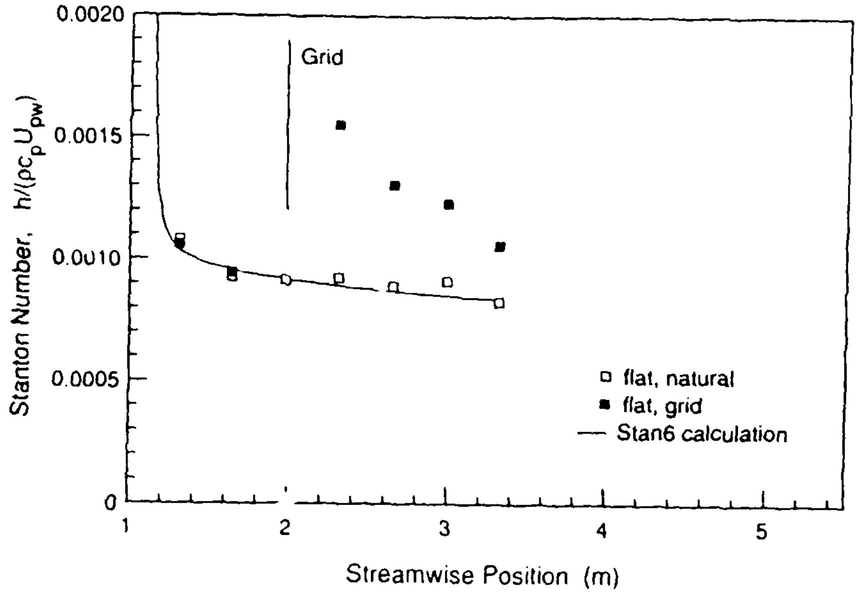

Figure 2a. Stanton number for the flat-plate section.

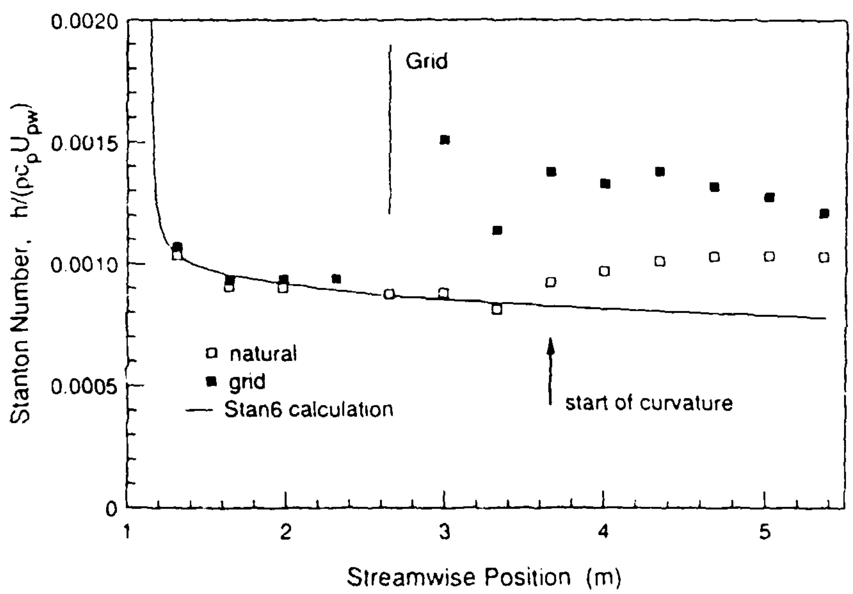

Figure 2b. Stanton number for the flat and curved sections.

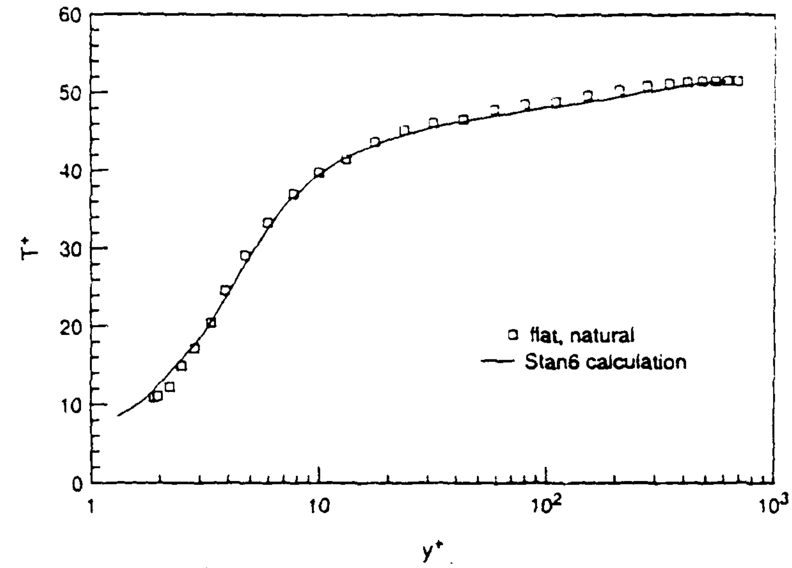

Figure 2c. Mean temperature profile.

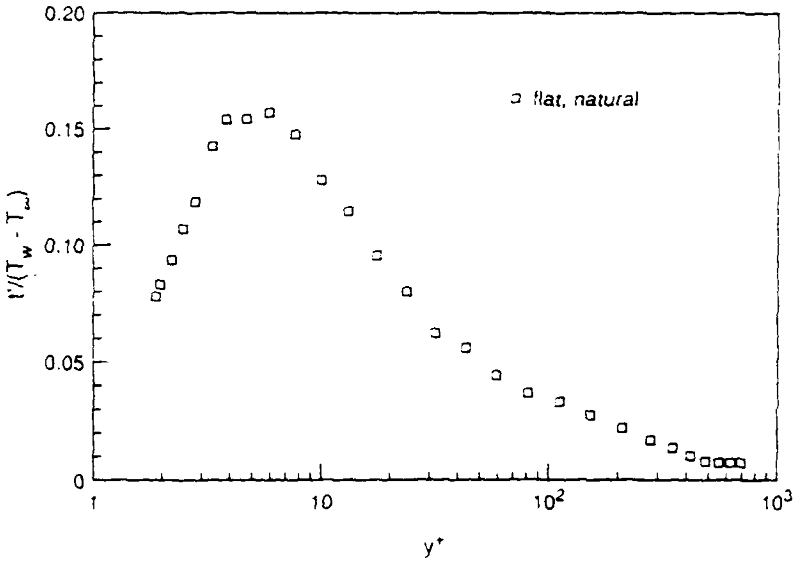

Figure 2d. Fluctuating temperature profile.

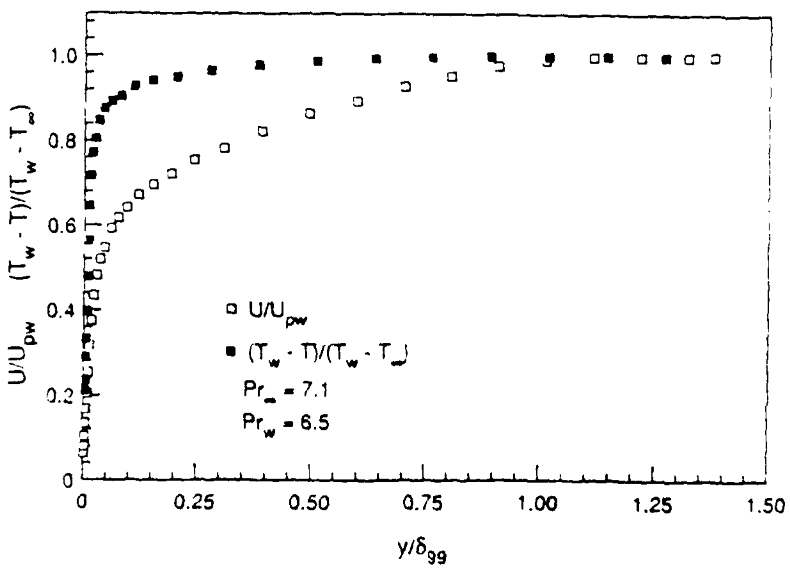

Figure 2e. Hydrodynamic and thermal profiles.

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